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Terahertz communication channel of healthcare applications: Performance analysis and improvement of internet of nano health things*

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A R T I C L E I N F O

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A B S T R A C T

Terahertz communication inside the human body uses minimal power; therefore, the destination may not receive the signal properly due to losses caused by molecular absorption and path loss. In this paper, we developed a new cooperative communication for the Internet of Nano Health Things (IoNHT), named the Best Path Selection in IoNHT (BPS-IoNHT). In addition, an innovative communication scenario for Nano Body Sensors Networks (NBSN) has been proposed. The proposed protocol has been thoroughly analysed and mathematically formulated regarding path loss, outage probability and bandwidth efficiency. The objective of the work is to reduce the outage probability and increase bandwidth efficiency. The results show that the proposed protocol performs better than recently published work. The outage probability has been reduced by 29%, and bandwidth efficiency improved by 35% compared to recent work.

1. Introduction

The healthcare systems future are histrionically developing with the acceleration of medical technologies. The attempt towards miniaturisation is making innovative solutions to guarantee superior effectiveness in diagnoses and treatments [1]. Such aspirations correlate with an strong progress in the nanotechnology field and the development of micro/nanoscale robotic systems. Magnetic nano-swimmers [2], bacteria-powered micro-robots [3] as well as ant-like nano-engines [4] are patterns of biologically inspired nanomachines. In the healthcare domain, nano-sensors can sense/detect any virus or harmful bacteria in the environment [5]. This can led to the progress of the Nuclear, Biological and Chemical defence system [6]. Eventually, the progress mentioned above in the various domains has paved the way towards in-vivo wireless nanosensor networks. These network techniques have been recently proposed to provide faster and more precise disease diagnosis and treatments compared to traditional technologies [7].

Both molecular and electromagnetic (EM) communications are leading wireless technologies that could allow communication between nanomachines. Despite the fact that molecular communication systems are being intensively studied [8], it suffers from low achievable data rates that radically limit nano-sensor networks' effectiveness. However, from an EM perspective, plasmonic nano-antennas have enabled wireless communication among nano-devices at high frequencies; it is still in its infancy, as most nano-sensing applications rely on light.

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Even though the THz frequency is promising communication band, it presents challenges such as absorption and spreading loss due to its high-frequency characteristics. It is necessary to employ a diversity technique, such as cooperative communication, to counteract these effects. There are several research papers published on aspects of in-vivo using cooperative communication methods. Some works considered the outage probability, bit error rate (BER) and energy efficiency. However, this paper focuses on cooperative communication with a relay selection technique. For the first time, this paper emphasises bandwidth efficiency, which is not considered in other work.

The analysis of the outage probability, BER and bandwidth efficiency are mainly rely on the channel modelling inside the human body. In the sequel, there are rich studies on the channel modelling inside the human body in the literature, where numerical analysis and characterisation of THz propagation through various body tissues have been studied and formulated in [9]. A novel model that consider intra-body signal degradation has been proposed in [10]. On other hand, a complementary multi-layer intra-body mathematical model for nano bio-sensing applications s presented in [11]. Alternatively, the authors in [12] advocated using the optical window for intra-body wireless communication among nanosensors with plasmonic nano-antennas. The communication channel's signal-to-noise ratio (SNR) is investigated in [13] for various power allocation methods. The maximum achievable data rate is deliberated to investigate the impairment of the signal inside the human body. In this paper, model of the [9] that is relied on various body tissues have been considering for analysing outage probability and bandwidth efficiency.

To date few works have been done on the outage probability for nano-communications system at THz band. The work conducted in the healthcare field in the nanoscale size is dedicated to improving the nanosensors networks' performance using different tools. In [14], the appearance of nano-electromagnetic communication systems provide an application in the NBAN. A new energy-aware communication paradigm of THz channel is designed that is relied on a clustering method which provide an improvement of NBAN performance. The new network paradigm is utilized to select optimum channel capacity. A closed-form expression for outage probability is also derived of the new conceptual design.

In [15], authors contribute with a hierarchical body area nano-network paradigm comprising from nano-devices and nano-routers, which are theoretically, designed utilizing industrially available electronic components. A traditional communications method working at the THz channel for transferring the information among nano-devices is analysed and mathematically formulated. The emerging of the Internet of Things (IoT), the usage of the internet has changed, as various types of objects, sensors, and devices can now interact, allowing our future networks to connect almost everything, from conventional network devices to people. A unified architectural model of nano-network with a layered method, network function virtualisation as well as IoT technologies, combining a software-defined network is presented in [16], where, major challenges in applying these functions with the nanotechnology paradigm and the open research issues were also addressed. Transmit power of an in-vivo sensor node needs to be minimised as high transmit power harms biological tissues inside the human body. Transmitted power optimisation is also considered for in-vivo sensor nodes operating at the THz band. The effect of blood, skin and fat on transferring the signals in an in-vivo communication network has been mathematically formulated using different modulation methods and compute received power by an on-body sensor node are presented in [17]. The threshold distance between two communicating nanonodes is calculated utilizing eigenvalues. It is further utilized as a constraint for particle swarm optimization (PSO) to optimise the transmitted power of the in-vivo nano-sensor.

To this end, cooperative communication can be considered an effective tool to mitigate the losses due to path loss and molecular absorption. In the literature, very few works investigated and studied cooperative communications. Only two examined outage probability in nanobody sensors networks (NBSN). The first was presented by [18], and the protocol of cooperative communication in the THz band regarding the outage was examined. According to graphical analysis, cooperative communication resulted in a ten-fold

Table 1
Comparison State of Arts—Cooperative Communication.

Pub. year [Ref. No.]	Protocols/methods	Metrics	Application	Limitation
2017 [18]	Traditional cooperative communication	• Outage probability	Healthcare application (in-vivo)	• No relay selection is utilised • Simple cooperative communication is used • Bandwidth efficiency is not considered
2021 [19]	Traditional cooperative communication	• Outage probability • BER	Healthcare application (in-vivo)	• No relay selection is utilised. • Simple cooperative communication is used. • Bandwidth efficiency is not considered
2017 [20]	Multi-relay network with best relay selection (BRS)	• Probability of error	No healthcare application	• Bandwidth efficiency is not considered • Healthcare application is not considered
2019 [21]	Multi-relay network with BRS	• Probability of error	No healthcare application	• Bandwidth efficiency is not considered • Healthcare application is not considered
Proposed Work	Best Path Selection in IoNHT (BPS-IoNHT)	• Outage probability • Bandwidth efficiency	Healthcare application (in-vivo)	• Relay selection with BPS is considered • Bandwidth is analysed and mathematically modelled • In-vivo application is considered.

boost in system performance.

The second work is presented in [19]; a cooperative communication method using amplify-and-forward (AF) and decode-and-forward (DF) for nanosensor communication inside the human body is proposed. Three important metrics have been considered, BER, outage probability and SNR. First, the results show that cooperative communication methods achieved better performance than non-cooperative ones; second, the DF method achieved better performance compared to AF methods by 5.68%, 24.51% and 80.9%, respectively.

In addition, two works used cooperative methods for nano communication but not in a healthcare application; in [20], a cooperative nano communication system is presented in the THz-gap frequency region. A single DF relay, a joined DF multiple relay system and BRS, and a DF multiple relay network with multiple hops with BRS showed the best outage probability for the proposed cooperative nano communication networks in the THz band.

Cooperative nano communication utilising the wireless power transfer protocol of the power switching relay and the time switching relay is suggested in [21]. The suggested cooperative nano communication networks' outage probability performances for a single DF relay, a joined DF multiple relay network and BRS, and a DF multiple relay network with multiple DF hops with BRS for wireless power transfer protocols, and switching relays have been studied. Comparison State of Arts of Cooperative Communication is given in Table 1.

Limitations of the previous works [19] can be elaborated as follows. The most straightforward cooperation protocols are used, whereas many other cooperative protocols can be used to obtain better outcomes. Only two metrics were considered, and one of the vital metrics, bandwidth efficiency, had not been analysed. Mathematical metrics were not analysed or investigated in either protocol. The proposed protocols burdened the existing nanosensors, which is not feasible for nanosensor networks.

To the best of these authors' knowledge, this work has not been investigated or analysed. We summarised our work as follows. A new Internet of Nano Health Things (IoNHT) was proposed and designed for NBSN, considering the signal journey from the inside of the human body to the cloud server. A new communication methodology is proposed for the NBSN, where nano-master nodes are included in the proposed structure, and those nano-master nodes will help the nano-sensors node to forward the information to a nano-router node. A new relay selection criteria and path selection are proposed. A Best Path Selection in IoNHT (BPS-IoNHT) is proposed, where two possible paths are considered, either dual-hop with a single nano-node master or a cooperative with the assistance of the two nano-master node. In addition, a novel selection criterion was proposed based on number of nano-master node and nano-sensors node and the it is mathematically formulated. A new metric has been analysed and formulated, bandwidth efficiency of the proposed A Best Path Selection in IoNHT (BPS-IoNHT), which is then improved for the NBSN. In addition, the outage probability has been mathematically formulated and driven. Finally, the proposed protocol shows superior performance compared to the works in the literature.

The outline of the paper is summarised as follows. Section 2 presents the proposed structure, which includes an NBSN in IoT and a communication structure is presented. A mathematical model of the proposed protocol of the outage probability is formulated in Section 3. In Section 4, the bandwidth efficiency was formulated and derived for the proposed protocol. Section 5 validates the proposed protocol against the proposed published works. Finally, the conclusion has been drawn in Section 6.

2. Proposed system structure and modelling

2.1. Nanobody sensors networks in the internet of nano health things (NBSN-IoNHT)

This subsection proposes and designs a new communication and the NBSN-IoNHT. Nano-sensors node have been distributed in specific areas inside the human body to detect and diagnose disease, harmful bacteria and viruses at early stages. Due to the technological advancements in electronic devices and IoT, nano-sensors node are integrated into standard and advanced networks. In this paper and as shown in Fig. 1, the proposed NBSN-IoNHT is described as follows:

Stage 1—nano-sensors node region: Nano-sensors node are embedded inside a human body to collect biological data. Nano-sensors node are distributed in a particular region with a nano-node master, which is larger and has a higher capacity than standard nano-

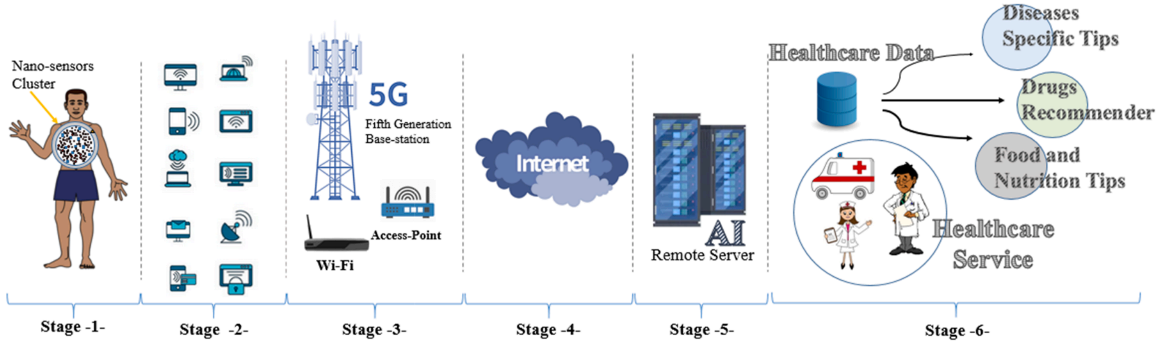

Fig. 1. General scenario of nanosensors for healthcare application.

sensors node. It has a transceiver, which allows it to receive and forward the data to a nano-router node. The nano-router node sends the received information to the on-body master node. The on-body master node cancels the noise from the received data and then forwards it to a smart device. Stage 2—smart device region: The smart device receives the forwarded information from the on-body node. It conducts analysis and provides feedback to the patient. In addition, the smart device forwards this data over a wireless medium to one of the wireless technologies, such as Wi-Fi, an access point or a base station. Stage 3 is the bridging link that connects the smart device to the internet backbone. Stage 4 is the internet backbone, which forwards the information to the intelligent cloud. Stage 5—the intelligent cloud: Here, a decision is made based on the received data from the patient. Stage 6 represents the medical service that will be provided for the patient, either remotely or locally.

2.2. Proposed communication structure of the NBSN in the IoT paradigm

The proposed protocol, BPS-IoNHT, is described in this subsection. However, before providing the details of the proposed protocol, let us explain the traditional communication scenario of the NBSN system. In the NBSN, the nano-sensor (S) node collect data from the environment inside the human body. Then it transmits the collected data to the nano-master (NM) node as shown in Fig. 2, Phase#1 transmission. The NM possess a higher battery source and processing ability. The NM, Phase#2 transmission, re-transmits the data to the master nano-router (NR) node, which may be located inside the human body (near the skin) or on the human body. What was proposed in [19] is traditional cooperative communication. The nanosensors collect the data from the environment and then transmit the collected data to the NM node and nearby nanosensors node (helper nanosensors node). Then the helper nanosensors node transmits the information received from the source to the NM, and finally, the NM forwards the data to the NR. Traditional cooperative communications are always cooperating, which is not feasible for nanosensors because it burdens the NBSN while utilising nanosensors for such cooperation.

The proposed Best Path Selection in IoNHT (BPS-IoNHT) in this paper is summarised as follows. First source nanosensors broadcast the data to two nearby NMs. Once the next master node, NM_n,correctly receives data from the source nanosensors, it provides a decision. If the maximum of the minimum of the $S - NM_n$ and $NM_n - NR$ links greater than a threshold value ζK_{thd}, where ζ is the index value of the number of the nano-master node, then the NM_n forwards the data to the nano-router. Otherwise, the MN_n asks the relay nano-master, NM_r, to send a copy of the data to the NM_n, then the NM_n combines both received signals using maximal ratio combining (MRC) and sends them to the nano-router. The proposed algorithm is given below:

Best-path selection algorithm procedures:

Procedure Best-Path Selection
Required: NM_n, NM_r, ζ, K_{thd}, k, $S - NM_n$ link and $NM_n - NR$ link
Definitions:
MN_n is the next nano-master node
MN_r is the relay nano-master node
ζ is the number of the nano-master node index
$K_{thd}$is a random variable of a particular distance d_{thd}
k is the number of nano-master node index
$S - NM_n$ is the link between the sensor and the next nano-master node
$NM_n - NR$ is the link between the next nano-master node and the NR

1. begin
2. SET ζ
3. SET K_{thd}
4. SET k
5. For i = k
6. SENSOR collects the data
7. SENSOR broadcasts the data
8. If one ***MN*** receives data correctly
9. ***NM*** is set as the next nano-master node,NM_n
10. NM_n sends ACK (positive acknowledgment) to the nearby ***NM***
11. nearby ***NM*** that also received data correctly is set as relay nano-master node, NM_r
12. If $S - NM_n$ and $NM_n - NR$ links that are greater than the threshold value ζK_{thd}
13. Then, NM_n forwards the data to the nano-router
14. Elseif $S - NM_n$ and $NM_n - NR$ links less than threshold value ζK_{thd}
15. Then, asks the relay nano-master, NM_r, to send a copy of the data to the NM_n
16. NM_n combines both received signals using MRC
17. NM_n sends a combined signal to the nano-router
18. Endif
19. Endfor

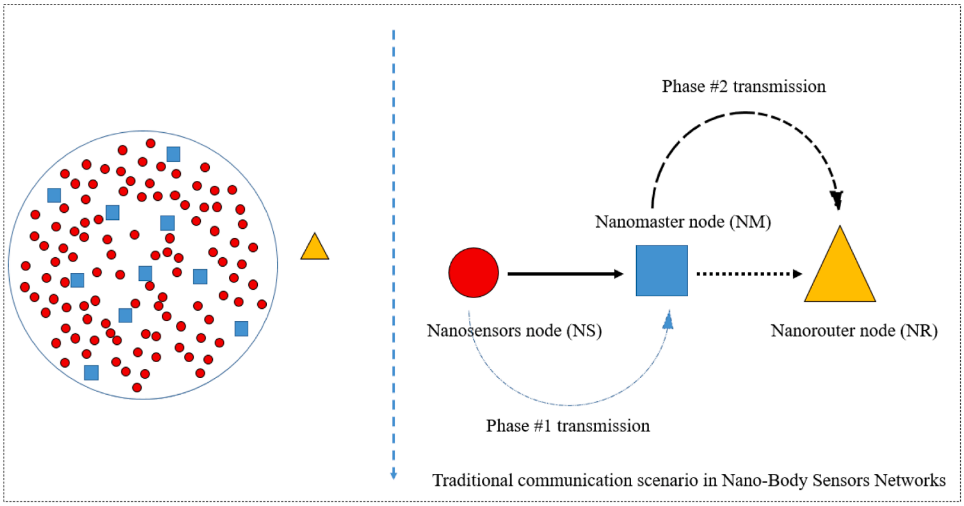

Fig. 2. Envisioned communication scenario of the NBSN inside the human body.

3. Mathematical model of the proposed protocol

3.1. Propagation model and outage probability

In this subsection, the propagation model with link analysis and outage probability over the $i - j$ link is described. The SNR of the $i - j$ link can be expressed as [9]:

$$\gamma_{i,j} = \frac{P_T}{P_N}\frac{\rho_{i,j}}{v_{i,j}} = SNR\frac{E\left[\rho_{i,j}\right]}{v_{i,j}} \tag{1}$$

where, P_T represents transmitted power by the source, P_N represents noise power and $\rho_{i,j}$represents the Gaussian random variable of the unit variance, $v_{i,j}$ represents path losses due to blood and tissue abortion. The calculation can be represented as [9]:

$$v_{i,j}(d,f) = -0.2N + 3.98 + (0.44N + 98.48)\,d_{i,j}^{0.65} + (0.068N + 2.4)f^{4.07} \tag{2}$$

in which N is the number of sweat ducts, $f$is the frequency in THz. $\rho_{i,j}$denoted as an exponentially distributed random variable with the mean value, $E\left[\rho_{i,j}\right] = d_{i,j}^{-\alpha}$, where $E[x]$denotes expectation and $d_{i,j}$ is the distance of the $i - j$ link, α represents the path-loss factor, and its values are between2and6.

First, consider direct transmission over i, j link. During this transmission, the instantaneous capacity $R(\gamma_{i,j}) = \log_2\left(1 + SNR\frac{E\left[\rho_{i,j}\right]}{v_{i,j}}\right)$, if the R_o is the threshold transmission rate, then the channel will be in outage whenever$R(\gamma_{i,j}) < Ro$, where $\{R(\gamma_{i,j}) < Ro\}$ is called the outage event. The outage probability can be mathematically expressed as [22]:

$$P_{i,j}^{out} = P\left(R\left(\gamma_{i,j}\right) \le Ro\right) = \left(1 - \exp\left(\frac{2^{Ro} - 1}{SNR}\frac{v_{i,j}}{d_{i,j}^{-\alpha}}\right)\right) \tag{3}$$

In what follows, the outage probability over $i - j$ for the large SNR can be expressed as [22]:

$$P_{i,j}^{out} = P(R \le Ro) = \frac{2^{Ro} - 1}{SNR}\frac{v_{i,j}}{d_{i,j}^{-\alpha}} \tag{4}$$

Followed by the successful transmission probability of the $i - j$ link can be expressed as:

$$P\left(R\left(\gamma_{i,j}\right) > Ro\right) = P_{i,j}^{s} = 1 - P_{i,j}^{out} = \exp\left(\frac{2^{Ro} - 1}{SNR}\frac{v_{i,j}}{d_{i,j}^{-\alpha}}\right) \tag{5}$$

3.2. Outage probability of the proposed protocols

3.2.1. Outage of the BPS-IoNHT

In this subsection, the proposed protocol, BPS-IoNHT, is formulated based on the description given in Section 2. In what follows, the outage probability of the BPS-IoNHT protocol can be expressed as:

$$P^{o}_{BPS-IoNHT} = \underbrace{P^{o}}_{Path\#1} P(\varphi_1) \cup \underbrace{P^{o}}_{Path\#2} \overline{P(\varphi_1)} = P(\varphi_1) \underbrace{P^{o}}_{Path\#1} + \underbrace{P^{o}}_{Path\#2} \overline{P(\varphi_1)} \tag{6}$$

in which, $\underbrace{P^{o}}_{Path\#1}$ is the outage probability of path#1, $S-NM_n$ and NM_n-MR links (all possible paths of the proposed protocol are shown in the Fig. 3), which represents a dual-hop transmission path, and this path is selected when the event $P(\varphi_1)$occurs. Where, $P(\varphi_1)$ is the probability of the maximum of the minimum of the $S-NM_n$ and NM_n-MR links greater than threshold value ζK_{thd}, where ζ is the index value of the number of the nano-master nodes, N_{mn}, and nano-sensors node, N_s, which is given as:

$$\zeta = \frac{N_{nm} - N_s}{N_s} \tag{7}$$

In sequel, the $P(\varphi_1)$ can be expressed as:

$$P(\varphi_1) = P\left(\zeta\, K_{thd} \geq K^{S-NM_n,NM_n-NR}_{max,min}\right) = 1 - \ P\left(\zeta\, K_{thd}\ \leq K^{S-NM_n,NM_n-NR}_{max,min}\right), \tag{8}$$

then,

$$K^{S-NM_n,NM_n-NR}_{max,min} = \underbrace{\text{argmaxmin}}_{k} \left\{\ (S-NM_n)_k,\ (NM_n-NR)_k\ \right\}$$

where, K_{thd} is a random variable of a particular distanced_{thd}, ζ is the number of nano-master index, $S-NM_r$ is the link from the nano-sensor node to the nano-master node, NM_r, that act as rely; then $S-NM_n$ is the link from the nano-sensor node to the next nano-master node, NM_r-NM_n is the link from the relay nano-master to the next nano-master node, and NM_n-NR is the link from the next nano-master node to the nano-router node. The cumulative distribution function (CDF) of two independent random variables can be expressed as:

$$P(\varphi_1) = 1 - \left(\exp\left(-d^{-\alpha}_{S-NM_n}\ \zeta\ K_{thd}\right)\ .\ \exp\left(-d^{-\alpha}_{NM_n-NR}\ \zeta\ K_{thd}\right)\right) \tag{9}$$

Taking the average of $P(\varphi_1)$ over K_{thd}, thus the average of the $P(\varphi_1)$ is expressed as:

$$P^{*}(\varphi_1) = \ 1 - \int_0^{\infty} \exp\left(-\zeta\ K_{thd}\left(\frac{1}{d^{-\alpha}_{S-NM_n}} + \frac{1}{d^{-\alpha}_{NM_n-NR}}\right)\right)\left(\frac{1}{K_{thd}}\right)\exp\left(-\frac{1}{d^{-\alpha}_{thd}}\ \zeta\ K_{thd}\right) dK_{thd}, \tag{10}$$

Then, locating the integration achieves:

$$P^{*}(\varphi_1) = \ 1 - \left(\frac{1}{\zeta} + \frac{d^{-\alpha}_{thd}}{d^{-\alpha}_{S-NM_n}} + \frac{d^{-\alpha}_{thd}}{d^{-\alpha}_{NM_n-NR}}\right)^{-1} \tag{11}$$

Up to here, path selection probability has been mathematically derived. The outage probability of path#2 can be expressed as:

$$P^{o}_{BPS-IoNHT} = \ P^{o}_{S-NM_n}\ P^{o}_{S-NM_r} + \left(1 - \ P^{o}_{S-NM_r}\ \right) P^{o,\ MRC}_{NM_r-NM_n} + \ P^{*}(\varphi_1)\left(1 - P^{o}_{S-NM_n}\right) P^{o}_{NM_n-NR} \ + \ \left(1 - P^{*}(\varphi_1)\right)\ \left(1 - \ P^{o,\ MRC}_{NM_r-NM_n}\right)\ P^{o}_{NM_n-NR}\ ,$$

$$P^{o}_{BPS-IoNHT} = \ P^{o}_{S-NM_n}\ P^{o}_{S-MN_r} + \left(1 - \ P^{o}_{S-NM_r}\ \right) P^{o,\ MRC}_{NM_r-NM_n} + \ \ P^{o}_{NM_n-NR}\ \left(P^{*}(\varphi_1)\left(1 - P^{o}_{S-NM_n}\right) + \left(1 - P^{*}(\varphi_1)\right)\ \left(1 - \ P^{o,\ MRC}_{NM_r-NM_n}\right)\ \right) \tag{12}$$

then,

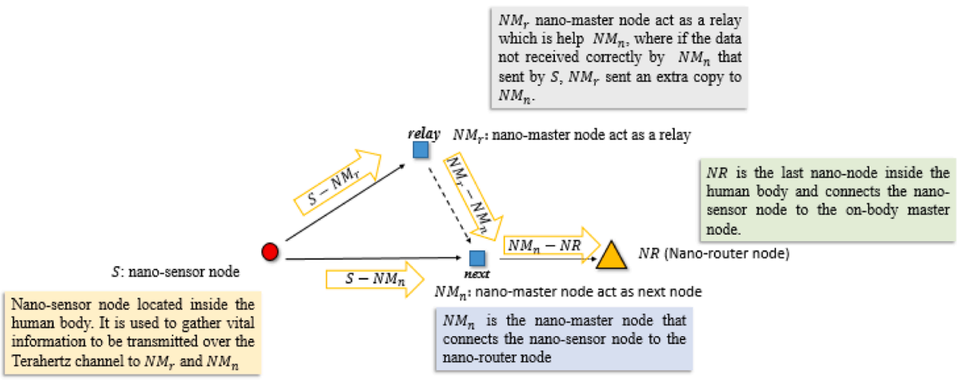

Fig. 3. Details of the links of the proposed BPS-IoNHT.

$$P^{o}_{S-NM_n} = 1 - \exp\left(\frac{2^{Ro}-1}{SNR}\ \frac{v_{S-NM_n}}{d^{-\alpha}_{S-NM_n}}\right), \tag{13}$$

$$P^{o}_{S-NM_r} = 1 - \exp\left(\frac{2^{Ro}-1}{SNR}\ \frac{v_{S-NM_r}}{d^{-\alpha}_{S-NM_r}}\right), \tag{14}$$

$$P^{o,\ MRC}_{NM_r-NM_n} = 1 - \left(\left(2^{Ro}-1\right)\sum_{i=1}^{2}\frac{1}{SNR}\ \frac{v_{NM_r-NM_n}}{d^{-\alpha}_{NM_r-NM_n}}\right), \tag{15}$$

$$P^{o}_{NM_n-NR} = 1 - \exp\left(\frac{2^{Ro}-1}{SNR}\ \frac{v_{NM_n-NR}}{d^{-\alpha}_{NM_n-NR}}\right), \tag{16}$$

$P^{o,\ MRC}_{NM_r-NM_n}$ is the outage probability after summing up the signal using MRC at the next nano-master node. Finally, by inserting (13), (14) and (15) in (12), we obtain the outage probability of the proposed protocol as:

$$\begin{aligned} P^{o}_{BPS-IoNHT} = {} & \underbrace{\left(1-\exp\left(\frac{2^{Ro}-1}{SNR}\frac{v_{S-NM_n}}{d^{-\alpha}_{S-NM_n}}\right)\right)}_{P^{o}_{S-MN_n}}\underbrace{\left(1-\exp\left(\frac{2^{Ro}-1}{SNR}\frac{v_{S-NM_r}}{d^{-\alpha}_{S-NM_r}}\right)\right)}_{P^{o}_{S-NM_r}}+ \\ & \underbrace{\exp\left(\frac{2^{Ro}-1}{SNR}\frac{v_{S-NM_r}}{d^{-\alpha}_{S-NM_r}}\right)}_{\left(1-\ P^{o}_{S-NM_r}\right)}\underbrace{\left(1-\left(\left(2^{Ro}-1\right)\sum_{i=1}^{2}\frac{1}{SNR}\frac{v_{NM_r-NM_n}}{d^{-\alpha}_{NM_r-NM_n}}\right)\right)}_{P^{o,MRC}_{NM_r-NM_n}} \\ & +\underbrace{\left(1-\exp\left(\frac{2^{Ro}-1}{SNR}\frac{v_{NM_n-NR}}{d^{-\alpha}_{NM_n-NR}}\right)\right)}_{P^{o}_{NM_n-NR}}\left[\underbrace{\left(1-\left(\frac{1}{\zeta}+\frac{d^{-\alpha}_{thd}}{d^{-\alpha}_{S-NM_n}}+\frac{d^{-\alpha}_{thd}}{d^{-\alpha}_{NM_r-NM_n}}\right)^{-1}\right)}_{P^{*}(\varphi_1)}\underbrace{\exp\left(\frac{2^{Ro}-1}{SNR}\frac{v_{S-NM_r}}{d^{-\alpha}_{S-NM_r}}\right)}_{1-P^{o}_{S-NM_n}}\right. \\ & \left.+\left(\underbrace{\left(\frac{1}{\zeta}+\frac{d^{-\alpha}_{thd}}{d^{-\alpha}_{S-NM_n}}+\frac{d^{-\alpha}_{thd}}{d^{-\alpha}_{NM_n-NR}}\right)^{-1}}_{1-\ P^{*}(\varphi_1)}\right)\underbrace{\left(\left(2^{Ro}-1\right)\sum_{i=1}^{2}\frac{1}{SNR}\frac{v_{NM_r-NM_n}}{d^{-\alpha}_{NM_r-NM_n}}\right)}_{1-P^{o,MRC}_{NM_r-NM_n}}\right] \end{aligned} \tag{17}$$

4. Bandwidth efficiency of proposed protocol

One of the critical metrics in the communication system is bandwidth efficiency. This paper defines bandwidth efficiency as the number of channels/slots required to transmit a single packet/frame to its destination. For example, to transmit a packet/frame over two hops, two channels/slots are required to reach the destination. Therefore, the bandwidth efficiency for the abovementioned case is 0.5 [23,24].

Per the information from the previous section, the mathematical model average bandwidth efficiency of the described protocol of the BPS-IoNHT is given below:

$$\begin{aligned} BE_{\text{BPS-IoNHT}} &= \frac{1}{2}\ P(\varphi_1)\ +\frac{1}{3}\ \overline{P(\varphi_1)}\ =\frac{1}{2}P(\varphi_1)\ +\frac{1}{3}\ (1-\ P(\varphi_1)), \\ BE_{\text{BPS-IoNHT}} &= \frac{1}{2}+\frac{1}{3}\ -\ \frac{1}{3}\ P(\varphi_1), \\ BE_{\text{BPS-IoNHT}} &= \frac{5}{6}\ -\ \frac{1}{3}P(\varphi_1) \end{aligned} \tag{18}$$

in which, $P(\varphi_1)$ is the probability that the $S-MN_r$ link is greater than the maximum of the minimum of the $S-NM_n$ and NM_n-NR links, then $P(\varphi_2)$ is the probability that the NM_r-NM_nlink is greater than the maximum of the minimum of the $S-NM_n$ and NM_n-NR links, which are given in (11) and (12), respectively. Additionally, $\overline{P(\varphi_1)}$ and $\overline{P(\varphi_2)}$ complements the probability of $P(\varphi_1)$and $P(\varphi_2)$, respectively, or it represents that the cooperative path is selected, and one of the nano-master nodes acts as a relay. With the help of (7) and (8), (18) can be revised as:

$$BE_{\text{BPS-IoNHT}} = BE_{\text{BPS-IoNHT}} = \frac{5}{6} - \frac{1}{3}\underbrace{\left(1 - \left(\frac{1}{\zeta} + \frac{d_{thd}^{-\alpha}}{d_{S-MN_n}^{-\alpha}} + \frac{d_{thd}^{-\alpha}}{d_{MN_n-MR}^{-\alpha}}\right)^{-1}\right)}_{P^*(\varphi_1)} \tag{19}$$

Eq. (19) proves that as the $P(\varphi_1)$and$P(\varphi_2)$ approach zero; the bandwidth efficiency is 0.333. On the other hand, as the $P(\varphi_1)$and$P(\varphi_2)$ approach one; the bandwidth efficiency is 0.5. As expected and observed from (16), direct communication between nano-sensor node and nano-master node can save and improve bandwidth efficiency. Therefore, using relay communication in the traditional nano-communication system of IoNHT is not always preferred. However, direct transmission between may not be reliable or offer better communication.

5. Results and discussion

This section evaluates the performance of the proposed protocol, BPS-IoNHT. In the simulations, a random topology of the nanosensors and nano-master nodes is located within an area of $1m \times 1m$, and the nano-router shares the same region. The distances are assumed variables between nanosensors, the nano-master node and the nano-router. In this simulation, the maximum number of 10 nanosensors is assumed within the nanosensors' particular region. The maximum number of nano-master nodes of 10 is assumed within the entire region, and all are managed by one nano-router. Each nano-sensor may connect to two or more nano-master nodes. All the nano-nodes are assumed to be static within $1m \times 1m$. The complete parameters of the simulation are listed in Table 2.

Fig. 4(a) represents the probability of the dual-hop selection vs distance $S - MN_n$ and $MN_n - MR$ links. As shown, the threshold distance, d_{thd}, is set to 0.25. Fig. 4(b) represents the threshold distance, d_{thd}, set to 0.75. There are three observations: 1) The probability of the dual-hop selection reduced as the distance of the $S - NM_n$ and $NM_n - NR$ links increased; in this case, the system used a relay master to help in the transmission; 2) The probability of the dual-hop selection increased as the ζ value reduced, where ζ represents the number of nano-master nodes ratio to the number of nano-sensor nodes within the same cluster. In this scenario, more nano-master nodes meant a higher probability of finding the best next nano-master node; 3) Minimal d_{thd} shows the probability of the dual-hop selection reduction due to a lower number of nano-master nodes within a particular cluster.

Fig. 5 represents bandwidth efficiency vs distance, $S - MN_n$ and $MN_n - MR$ links. Fig. 5(a) represents the threshold distance, d_{thd}, set to 0.25, and Fig. 5(b) shows the threshold distance, d_{thd}, set to 0.75. There are four observations: In all cases, the bandwidth efficiency of the proposed protocol is more efficient than the protocol proposed in [23]. First observation, the bandwidth efficiency reduced as the distance of the $S - NM_n$ and $NM_n - NR$ links increased; in this case, the system used a relay master to assist in the transmission. For this reason, three slots are used for transmitting a single packet instead of two slots. The second observation regarding the bandwidth efficiency protocol approach proposed in [23] demonstrates that bandwidth efficiency increased as the ζ value was reduced, where ζ represents the number of nano-master nodes ratio to the number of nano-sensor nodes within the same cluster. In this scenario, more nano-master nodes meant a higher probability of finding the best next nano-master node. For this reason, the system that used a dual-hop transmission instead of a cooperative transmission increased its bandwidth efficiency. The third observation was that d_{thd} increased, meaning the bandwidth efficiency increased. Because a higher number of nano-master nodes fall within a particular cluster, the proposed protocol will select a dual-hop transmission over cooperative communication.

Fig. 6 represents outage probability vs distance SNR. In Fig. 6(a), the threshold distance, d_{thd}, is set to 0.25, and in Fig. 6(b), the threshold distance, d_{thd}, set to 0.75. In all cases, the outage probability of the proposed protocol is better than the protocol proposed in [23]. The figures above provide three observations: 1) The outage probability reduced as the SNR increased; 2) The outage probability reduced as the ζ value reduced, where ζ represents the number of nano-master nodes ratio to the number of nano-sensor nodes within the same cluster. Again, in this scenario, more nano-master nodes meant a higher probability of finding the best next nano-master node; however, the most efficient link is established, and the outage probability is reduced; and 3) That d_{thd} increased, meaning outage probability increased because having fewer nano-master nodes within the cluster minimises locating the optimal next master node dramatically.

Table 2
Simulation Parameters.

Symbol	Definition	Value
N	Number of sweat ducts [19]	3
R_o	Threshold transmission rate [23]	2 b/s/Hz
NM	Maximum number of nano-master nodes	10
α	Path-loss factor [24]	2 – 6
NS	Maximum number of nano-sensor nodes sharing the same transmission range	10
NR	Number of nano-router nodes	1
f	Frequency [19]	0.95THz

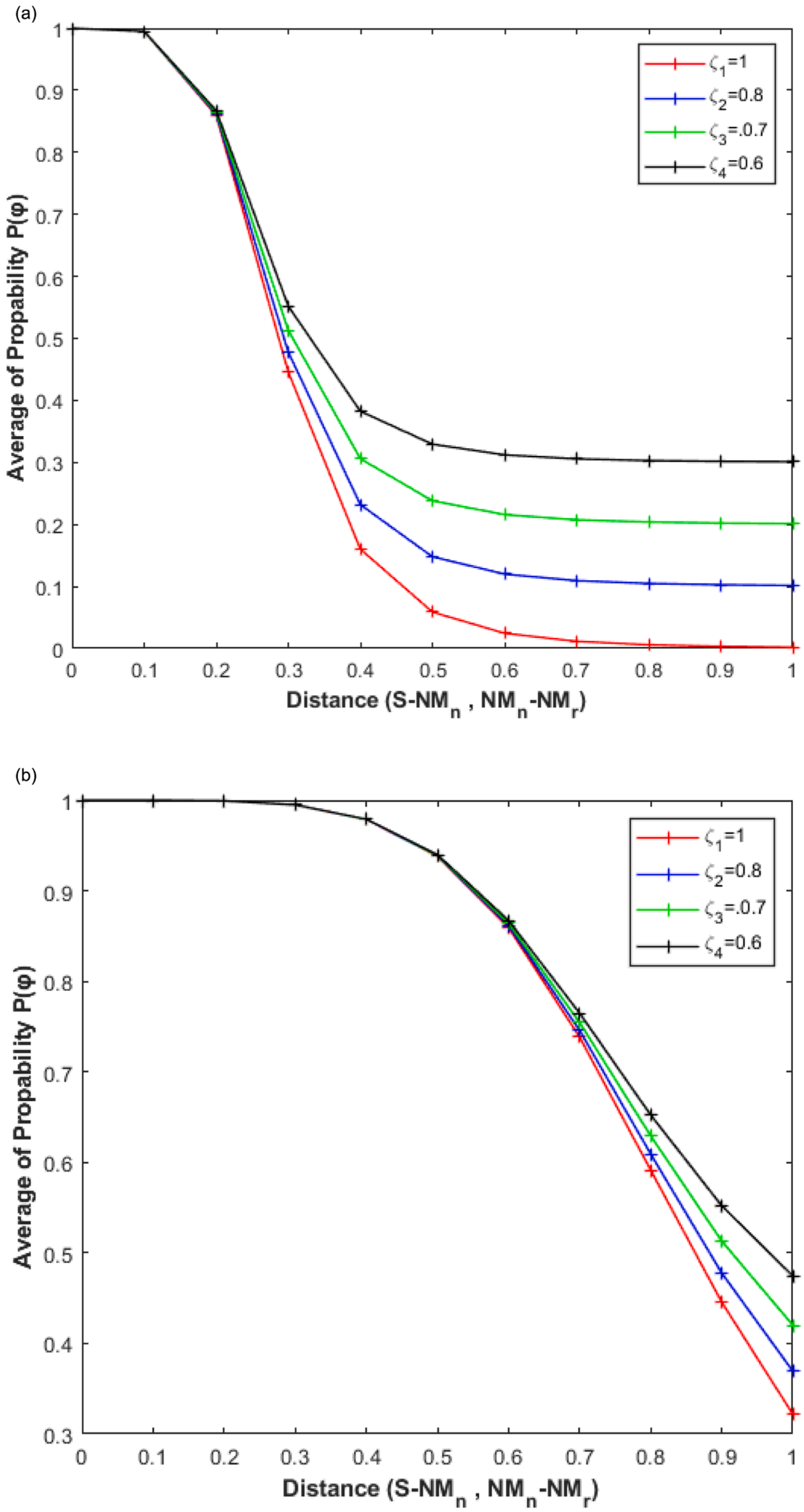

Fig. 4. (a): Threshold Distance: d_{thd}, set to 0.25 (b): Threshold Distance: d_{thd}, set to 0.75.

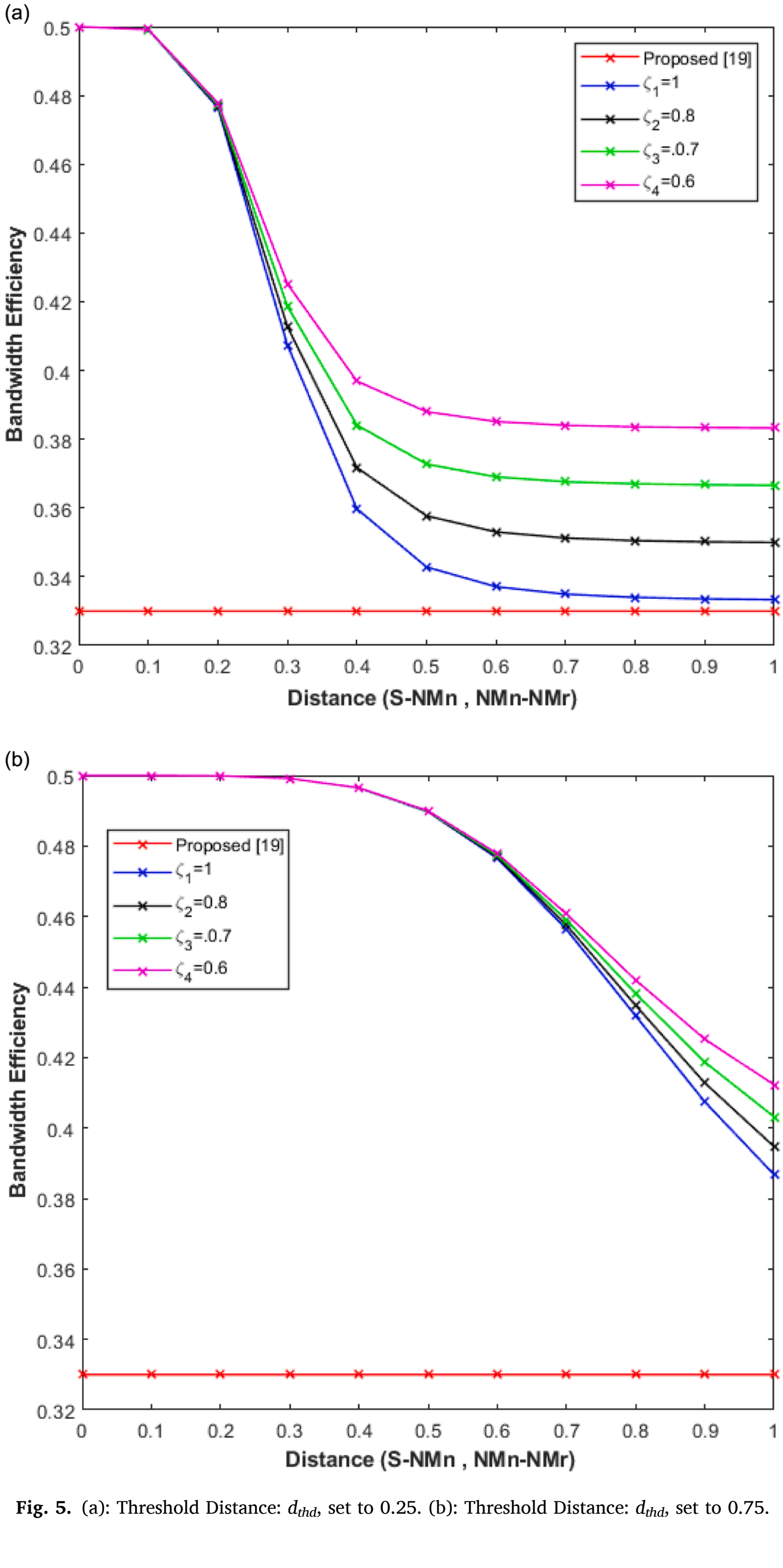

Fig. 5. (a): Threshold Distance: d_{thd}, set to 0.25. (b): Threshold Distance: d_{thd}, set to 0.75.

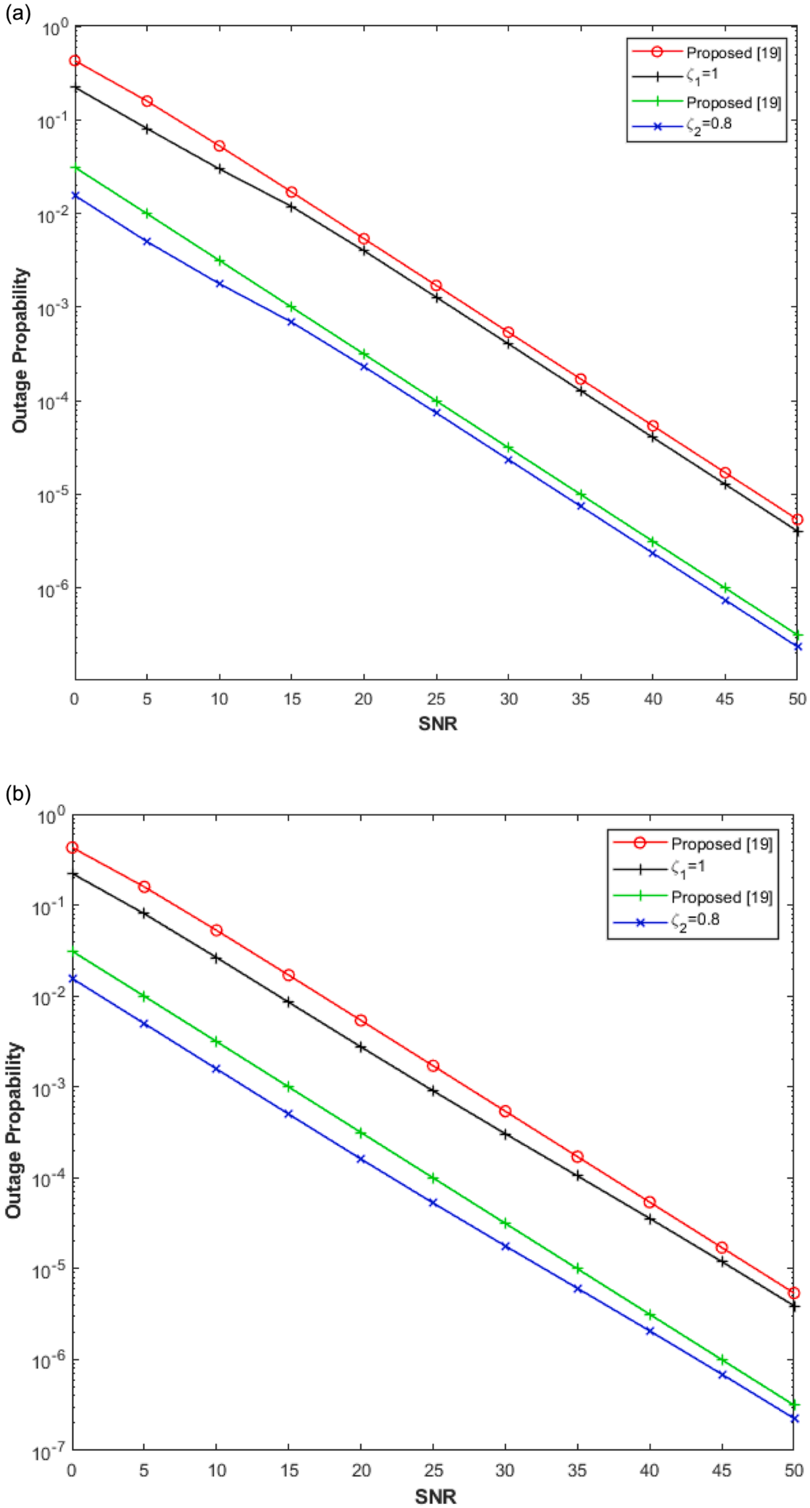

Fig. 6. (a): outage probability vs distance SNR; Threshold distance, d_{thd}, is set to 0.25. (b): outage probability vs distance SNR; Threshold distance, d_{thd}, is set to 0.75.

6. Conclusion

Recent advancements in micro/nano devices and network design are encouraging the development of a new paradigm to improve the healthcare system known as NBSN-IoNHT. An innovative nano communication protocol that supports reliable data transmission, which is named as BPS-IoNHT is proposed. The proposed protocol adaptively constructs choices between dual-hop communications or cooperative communications based on the proposed selected metrics. This paper selected two critical metrics, outage probability and bandwidth efficiency; both metrics have been mathematically modelled and investigated. The conclusions demonstrate that the proposed protocol achieved superior performance compared to existing work regarding outage probability and bandwidth efficiency. Future studies should analyse the proposed protocol combined with an energy-harvesting technique that allows the nano-master node to reap the energy and then cooperate rely on a time switch system.

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Declaration of Competing Interest

No author associated with this paper has disclosed any potential or pertinent conflicts which may be perceived to have impending conflict with this work.

Data availability

No data was used for the research described in the article.

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